Discovery of the "missing" mode in HR 1217 by the Whole Earth Telescope

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ABSTRACT

HR 1217 is a prototypical rapidly oscillating Ap star that has presented a test to the theory of nonradial stellar pulsation. Prior observations showed a clear pattern of five modes with alternating frequency spacings of 33.3 μHz and 34.6 μHz, with a sixth mode at a problematic spacing of 50.0 μHz (which equals $1.5 \times 33.3\mu$Hz) to the high-frequency side. Asymptotic pulsation theory allowed for a frequency spacing of 34 μHz, but HIPPARCOS observations rule out such a spacing. Theoretical calculations of magnetoacoustic modes in Ap stars by Cunha (2001) predicted that there should be a previously undetected mode 34 μHz higher than the main group, with a smaller spacing between it and the highest one. In this Letter, we present preliminary results from a multi-site photometric campaign on the rapidly oscillating Ap star HR 1217 using the "Whole Earth Telescope". While a complete analysis of the data will appear in a later paper, one outstanding result from this run is the discovery of a newly detected frequency in the pulsation spectrum of this star, at the frequency predicted by Cunha (2001).

Key words: Stars: oscillations – stars: variables – stars: individual (HR 1217) – stars: magnetic.

1 INTRODUCTION

After decades of trying, the search for solar-type oscillations in stars finally appears to have been successful (see, e.g., Bouchy & Carrier 2001 and Carrier et al. 2001). Although this led Gough (2001) to announce the "birth of asteroseismology", for the past two decades asteroseismology has successfully investigated the interiors of many types of stars other than the solar-type stars. Remarkable success stories of observational and theoretical investigations of white dwarf stars and rapidly oscillating Ap stars have amply demonstrated the power of asteroseismology as a tool to advance our knowledge of the physics of stellar interiors and the details of stellar evolution (see, e.g., Kurtz et al 1989; Winget et al. 1991; Kawaler & Bradley 1994; Matthews et al. 1999).

With these successes, some mysteries have remained. In this Letter, we address apparently contradictory interpretations of the pulsation spectrum of the rapidly oscillating Ap star HR 1217. This star, discovered to be a pulsator by Kurtz (1982), was investigated with an extensive global campaign in 1986 (Kurtz et al. 1989). A key result from that data set was a list of six principal pulsation frequencies, reproduced in Table 1. As expected from the asymptotic theory of nonradial pulsations, five of the modes are nearly equally spaced in frequency.

The asymptotic frequency spacing, ν_o, is a measure of the sound crossing time of the star, which in turn is determined by the star's mean density and radius. With a typical mass of Ap stars of about $2\mathrm{M}_\odot$, ν_o reflects the radius of the star, with ν_o scaling as $R^{-3/2}$. In the asymptotic limit, the number of nodes in the radial direction, n, is larger than the spherical degree ℓ. Assuming adiabatic pulsations in spherically symmetric stars the pulsation frequencies are, to first order,

$$\nu_{n,\ell} = \nu_o(n + \ell/2 + \epsilon),$$

where ϵ is a (small) constant (Tassoul 1980, 1990). Without precise identification of the degree (ℓ) of the pulsation modes, asymptotic theory allows the frequency spacing to be uncertain by a factor of two, depending on whether modes of alternating even and odd ℓ are present (producing modes separated by $\nu_o/2$ in frequency), or only modes of consecutive n.

The results of the 1986 campaign were inconclusive as to whether ν_o was 68 μHz or 34 μHz. The prinicipal frequencies seen in the data are given in Table 1; they correspond to those found by Kurtz et al. (1989) for the 15 day stretch of best coverage (for comparison with the new data presented in Table 3). The highest frequency of HR 1217 in those data was 50 μHz higher than the fifth mode, suggesting that ν_o was 34 μHz. But the fine structure of the spacings was suggestive of alternating ℓ values. Fortunately, the two possible values could be assessed if the luminosity of the star were precisely known. If ν_o were 34 μHz, then the radius of HR 1217 would be large enough that it would be far removed from the main sequence (i.e. more evolved) and therefore more luminous (Heller & Kawaler 1988). Matthews et al. (1999) used the HIPPARCOS parallax measurement to place HR 1217 unambiguously close to the Main Sequence – meaning that ν_o is indeed 68 μHz. This deepened the "mystery of the sixth frequency", now $\frac{3}{4}\nu_0$ higher. No clear theoretical construct could explain it.

The asymptotic frequency spacing given in the equation above is valid only for linear adiabatic pulsations in spherically symmetric stars. However, the magnetic field, the chemical inhomogeneities, and rotation all contribute to break the spherical symmetry in roAp stars. Therefore, it is important to know the effects that these deviations from spherical symmetry have on the theoretical amplitude spectra of roAp stars, before comparing the latter with the observed amplitude spectra. The effects of the chemical inhomogeneities have been discussed recently by Balmforth

Table 1. Principal frequencies in HR 1217 (data from Kurtz et al. 1989).

Number	frequency [μHz]	frequency spacing [μHz]	amplitude [mmag]
f1	2619.51±0.05	-	0.28±0.03
f2	2652.92±0.02	33.41±0.05	1.09±0.03
f3	2687.58±0.03	34.66±0.04	0.94±0.03
f4	2721.02±0.02	33.44±0.04	1.16±0.03
f5	2755.49±0.04	34.47±0.04	0.49±0.03
f6	–	–	< 0.09
f7	2806.26±0.06	50.77±0.07	0.25±0.03

et al. (2001), but those will not concern us further here. The effects of the magnetic field on the oscillations of roAp stars (Dziembowski & Goode 1996; Bigot et al. 2000; Cunha & Gough 2000), as well as the conjoined effect of rotation and magnetic field (Bigot 2002), have been determined by means of a singular perturbation approach. While generally the magnetic field effect on the oscillations is expected to be small, Cunha & Gough (2000) found that, at the frequencies of maximal magnetoacoustic coupling, the latter is expected to become significantly large, resulting in an abrupt drop of the separation between mode frequencies.

The observational consequence of the results of Cunha & Gough (2000) suggests that we should see equally spaced modes in roAp stars, with an occasional mode much closer to its lower frequency counterparts. More recently, Cunha (2001) suggested that the explanation of the strange separation between the last two modes observed in HR 1217 could rest on the occasional abrupt decrease of the large separations predicted by Cunha & Gough (2000). For this prediction to hold, she argued that the observations of Kurtz et al. (1989) must have missed detecting a mode at a frequency 34μHz higher than that of the fifth mode they observed. She predicted that new, more precise measurements would find this "missing mode" if the Alfvénic losses were not large enough to stabilise it. Detailed re–examination of the data from 1986 shows no peak at the key position approximately 33 μHz above f5 at the 0.1 mma level.

In 2000 November, we began an extensive, coordinated global photometry campaign on HR 1217 using the Whole Earth Telescope. A complete analysis of this extensive data set, which addresses many other aspects of roAp stars, is in preparation. In this Letter, we present a preliminary analysis of data from that run that clearly shows a previously unseen pulsation mode at a frequency about 36 μHz above the fifth frequency, as predicted by Cunha (2001). In the next section, we describe the observational procedures and the data coverage and reduction. Section 3 presents the preliminary frequency analysis, and the results are discussed in Section 4, along with a brief discussion of the impact of this result on the theory of pulsations of roAp stars.

2 OBSERVATIONS

The WET run on HR 1217 began on 2000 November 6 at selected sites, and continued through early 2000 December. The bulk of the data, with the best global coverage, were obtained during 2000 November 14-30. A complete analysis of all of the available data is currently underway. For this Letter, we concentrate on the central portion of the WET run, with data from five sites. This subset of the full data set provides high signal–to–noise and a reasonable global coverage. It also extends over slightly more than one rotation cycle of HR 1217. Since the pulsation amplitude is modulated with the rotation period, this data subset is just long enough to begin to resolve rotational sidelobes of the main peaks.

Table 2 lists the individual observing runs in this data set. The telescopes used range in aperture from 0.6 m to 2.1 m. Data from all sites were obtained using photoelectric photometers, with 10 s individual integrations. At Beijing Astronomical Observatory, McDonald Observatory, Mauna Kea Observatory, and Observatorio del Teide, the observers used three-channel photometers that are functionally similar to the equipment described in Kleinman et al. (1996). The South African Astronomical Observatory observations were made with a single-channel photometer, and the observations at CTIO with a two–channel photometer. At all sites, observations were made through a Johnson B filter, along with neutral density filters when needed to keep the count rates below $10^6\,\mathrm{s}^{-1}$. Following the procedures described in Kleinman et al. (1996), the sky background was continuously monitored with the three-channel instruments. At sites using two-channel and single channel photometers, the sky was obtained several times during the night at irregular intervals, and then interpolated during reduction.

As can be seen in Table 2, we obtained 215.2 hr of observations during the interval from 2000 November 14–30, resulting in a duty cycle of 53%. Longitude coverage was adequate, though the longitudes around central Asia were not as well covered as the others.

3 FREQUENCY ANALYSIS

The Fourier transform (FT) of the reduced data, in the frequency range where the pulsations are significant, is shown in in the top panel of Figure 1. The spectral window, shown in the middle panel of the figure, shows the response of the FT to a single, noise-free sinusoid sampled at the same times as the light curve of HR 1217. The side peaks correspond to aliases of $1\,\mathrm{d}^{-1}$ and $2\,\mathrm{d}^{-1}$. They are approximately 40% of the amplitude of the principal peak, and are caused by the (small) daily gaps present in the data causing incomplete global coverage.

The principal periodicities that we found in HR 1217 are listed in Table 3. Following initial identification of the main peaks in the FT, we did a successive least-squares fit to the light curve including all of the main peaks. We then included the rotational sidelobes in the fit, sequentially. Throughout this process we prewhitened the data by removing noise-free sinusoids at the fitted frequencies, amplitudes, and phases. We stopped when none of the remaining peaks was above

Table 2. Observing log of selected high-speed photometry of HR 1217 from the Whole Earth Telescope Extended Coverage Campaign 20 (WET Xcov20)

Run Name	Date 2000	Start (UT)	Run (hr)	Observatory	Tel (m)
sa-od044	Nov 14	21:03:00	5.04	SAAO	1.9
mdr-142	Nov 15	01:28:10	5.06	CTIO	1.5
sa-od045	Nov 15	19:20:00	7.05	SAAO	1.9
teide01	Nov 16	00:42:10	3.56	Teide	0.8
mdr-143	Nov 16	01:23:00	7.23	CTIO	1.5
no1700q2	Nov 17	07:28:00	3.38	Mauna Kea	0.6
mdr-144	Nov 17	20:26:06	7.54	CTIO	1.5
teiden04	Nov 17	22:09:10	6.05	Teide	0.8
no1800q1	Nov 18	07:22:30	4.25	Mauna Kea	0.6
teiden05	Nov 18	22:53:20	5.40	Teide	0.8
sa-od047	Nov 18	23:29:00	1.45	SAAO	1.9
no1900q2	Nov 19	10:14:20	3.85	Mauna Kea	0.6
sa-od048	Nov 19	18:55:00	7.15	SAAO	1.9
teiden06	Nov 19	22:05:30	6.06	Teide	0.8
no2000q1	Nov 20	07:37:00	6.07	Mauna Kea	0.6
sa-od049	Nov 20	18:51:00	7.30	SAAO	1.9
sa-m0003	Nov 21	19:26:50	6.67	SAAO	0.75
sa-m0004	Nov 22	18:28:20	7.65	SAAO	0.75
no2300q1	Nov 23	07:15:50	4.59	Mauna Kea	0.6
teiden10	Nov 23	22:05:40	5.47	Teide	0.8
sa-m0006	Nov 24	18:18:00	7.76	SAAO	0.75
no2500q1	Nov 25	07:03:00	6.67	Mauna Kea	0.6
teiden12	Nov 25	22:09:20	5.61	Teide	0.8
joy-012	Nov 26	03:55:50	4.10	McDonald	2.1
no2600q2	Nov 26	06:59:30	6.47	Mauna Kea	0.6
sa-m0007	Nov 26	18:28:40	7.42	SAAO	0.75
no2700q1	Nov 27	06:38:00	5.55	Mauna Kea	0.6
jxj-0127	Nov 27	13:44:10	4.75	Beijing AO	0.85
sa-m0008	Nov 27	18:27:50	7.57	SAAO	0.75
teiden14	Nov 27	22:28:20	3.72	Teide	0.8
sa-h-046	Nov 28	18:54:30	6.41	SAAO	1.9
teiden15	Nov 28	22:01:50	5.52	Teide	0.8
no2900q1	Nov 29	06:41:00	6.77	Mauna Kea	0.6
sa-gh465	Nov 29	20:30:30	5.14	SAAO	1.9
teiden16	Nov 29	21:18:50	2.59	Teide	0.8
joy-028	Nov 30	03:54:20	5.24	McDonald	2.1
no3000q1	Nov 30	06:40:50	6.77	Mauna Kea	0.6
sa-gh466-9	Nov 30	19:30:20	6.26	SAAO	1.9
		Total	215.2		

the noise level. In all, we found 14 significant periodicities in this data set. In addition to the 7 principal frequencies, both rotational sidelobes of f3 and f4 were found. We also found the low-frequency rotational sidelobe of f2, f5, and f7. The frequencies listed in Table 3 are from the fit that included all 14 frequencies.

The bottom panel of Fig. 1 shows the FT of the residual light curve following the removal of 14 frequencies, on the same scale as the top panel. There are some residual peaks in this plot at interesting frequencies. Analysis of the full data set, including runs outside of the subset that we used, shows that some of these are real. They will be described in further detail in the full analysis of the data which is in preparation.

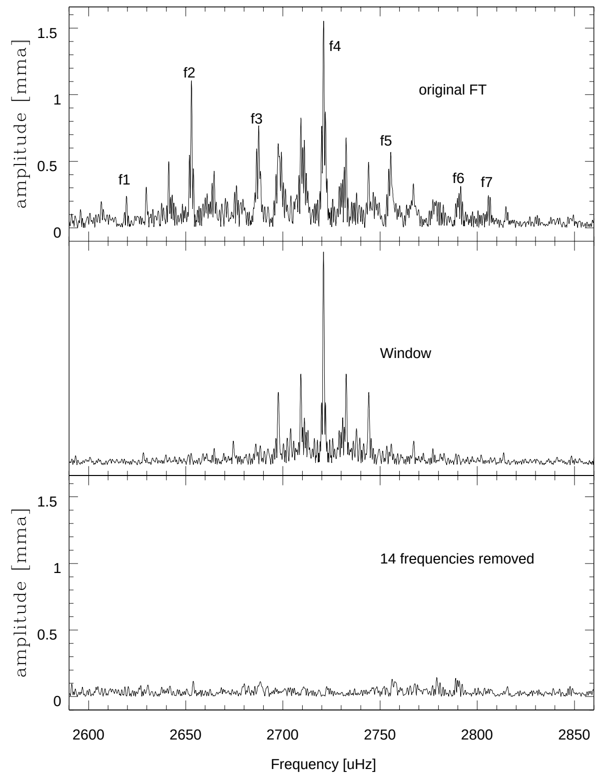

Figure 1. The Fourier transform of the subset of WET data used in our analysis. The top panel shows the FT of the data, the middle panel shows the spectral window, and the bottom panel shows the resulting FT after the data are prewhitened by 14 frequencies. The unit mma means milli-modulation amplitude which is measured in parts per thousand in intensity units. For amplitudes as small as these here, it is very nearly equivalent to mmag.

Table 3. Principal frequencies in HR 1217 in 2000

Number	frequency [μHz]	frequency spacing [μHz]	amplitude [mma]
f1	2619.51 $\pm$0.03	-	0.24 $\pm$0.02
f2	2652.96 $\pm$0.01	33.45 $\pm$0.04	0.95 $\pm$0.02
f3	2687.58 $\pm$0.02	34.62 $\pm$0.02	0.68 $\pm$0.03
f4	2720.96 $\pm$0.02	33.38 $\pm$0.03	1.29 $\pm$0.02
f5	2755.35 $\pm$0.03	34.39 $\pm$0.04	0.34 $\pm$0.02
f6	2791.48 $\pm$0.03	36.13 $\pm$0.04	0.29 $\pm$0.02
f7	2806.43 $\pm$0.14	14.95 $\pm$0.14	0.22 $\pm$0.07

4 RESULTS

4.1 Comparison with the 1989 data

Early in the run, it became clear that HR 1217 was pulsating with the same frequencies that were present in the 1986 data analysed by Kurtz et al. (1989). Tables 1 and 3 show that the principal frequencies from the 1986 study (f1 through f5 and f7) are highly consistent over a time span of 15 yr. Some of the amplitudes of these modes are higher in 2000 and some lower by small amounts than they were in 1986,

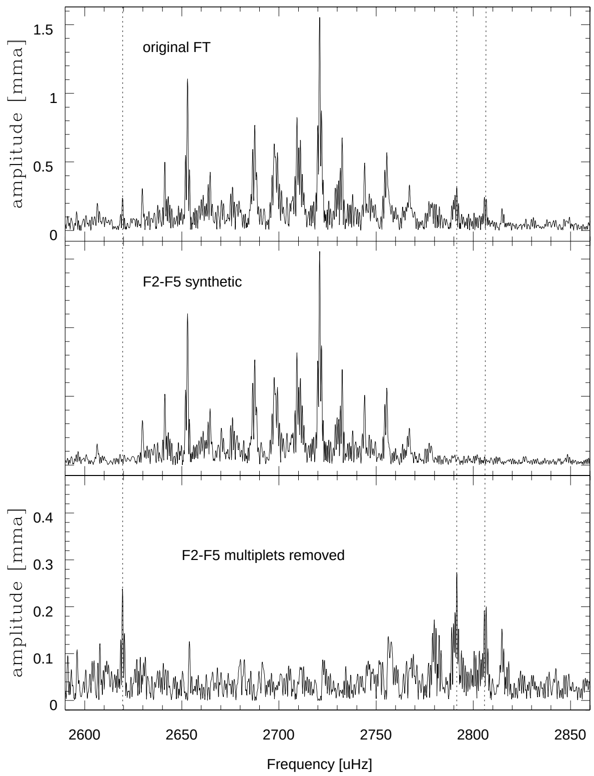

Figure 2. The Fourier transform of the subset of WET data used in our analysis. The top panel shows the FT of the data. The middle panel is a simulation of the FT that includes 10 frequencies - f2 through f5 along with their rotational sidelobes. The bottom panel shows the FT of the data prewhitened by those 10 frequencies. Vertical dotted lines show the position of f1, f6, and f7.

but it is the frequencies (and presence or absence) of the modes that are of interest here.

The chief difference between the 2000 data and 1986 data is the presence of a frequency at 2791 μHz listed as f6 in Table 3. That mode was not detected in the data of Kurtz et al. (1989 - Table 1) but was a clear signal in the WET Xcov20 2000 data. To ensure that this frequency is not an artefact of the data reduction algorithm, we repeated the frequency analysis of our data fitting just the large-amplitude peaks f2, f3, f4, and f5, and their rotational sidelobes (if present). We then removed those 10 frequencies. The results are illustrated in Fig. 2. This figure shows the original FT, and the FT of the data simulated by including f2-f5 and their rotational sidelobes. Clearly, there is excess signal at the positions of f1 and f7, but also at 2791 μHz as well.

Thus we conclude that the "new" frequency, f6, is real. Table 3 shows that it lies at nearly $\nu_o/2$ above f5, as expected if it is a normal $p-$mode and $\nu_o \approx 68\mu$Hz. It is much closer to f7 than $\nu_o/2$, as predicted by Cunha (2001).

4.2 Implications for roAp stars

Cunha (2001) speculated that the position of the f7 peak in the Kurtz et al. (1989) data is consistent with her model of the normal mode structure in Ap stars when magnetic fields are important to the pulsation dynamics. Since that peak was $\frac{3}{4}\nu_0$ above f5 (which is inexplicable in asymptotic theory), she suggested that there should be a peak at $\nu_o/2$ above f5. That is precisely what we see in the data from the WET run in November 2000 with the discovery of f6.

As discussed earlier, other explanations for the frequency spacing pattern from f5 to f7 are in direct conflict with the now well-determined HIPPARCOS luminosity of HR 1217. We therefore conclude that the frequency pattern in HR 1217 suggests that the pulsations we see in this star are consistent with normal $p-$mode pulsations whose frequencies are, in some cases, strongly affected by the magnetic field of the star.

Cunha (2001) suggested that large Alfvénic losses could help explain the missing f6 in the 1986 data, as these losses are maximal at the frequencies where the large separations experience the abrupt decrease. This energy loss could either stabilize the mode or contribute to decrease its amplitude (although it is not clear how the growth rates relate to the amplitude of the modes in roAp stars).

Since f6 is observed in the present data, the possibility that the Alfvénic losses are large enough to stabilise this mode can be ruled out, at least at the time of these observations. Whether at the time of the previous observations the efficacy of the magnetoacoustic coupling (which depends, among other things, on the exact frequency of the mode and on the characteristics of the magnetic field) was different, is something to which we do not have an answer. An attempt to monitor the amplitude of f6, as well as that of the other modes, in the future might, therefore, be worthwhile. However, the magnetic field does produce an important observable effect on the frequency of f7.

With the detection of f6, we move closer to a detailed understanding of the pulsation mechanism in roAp stars. Most intriguingly, this result for HR1217 suggests that, with appropriately detailed models, we may soon be able to probe the magnetic field structure below the surfaces of these stars through their pulsation frequencies – another application of asteroseismology to probing stellar interiors.

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REFERENCES

Balmforth, N.J., Cunha, M.S., Dolez, N., Gough, D.O., Vauclair, S., 2001, MNRAS, 323, 362

Bigot, L., 2002, in Radial and Nonradial Pulsations as probes of Stellar Physics, IAU colloquium 185, eds. C. Aerts, J. Christensen-Dalsgaard and T. Bedding, ASP Conf. Ser., in press

Bigot, L., Provost, J., Berthomieu, G., Dziembowski, W.A., Goode, P.R., 2000, A&A, 356, 218

Bouchy, F., Carrier, F., 2001, A&A, 374, 5

Carrier, F., Bouchy, F., Kienzle, F., Bedding, T.R., Kjeldsen, H., Butler, R.P., Baldry, I.K., O'Toole, S.J., Tinney, C.G., Marcy, G.W., 2001, A&A, 378, 142

Cunha, M.S., 2001, MNRAS, 325, 373

Cunha, M.S., Gough, D., 2000, MNRAS, 319, 1020

Dziembowski, W., Goode, P.R., 1996, ApJ, 458, 338

Gough, D.O., 2001, Science, 291 (5512), 2325

Heller, C.H., Kawaler, S.D., 1988, ApJL, 329, L43

Kawaler, S.D., & Bradley, P.A. 1994, ApJ, 427, 415

Kleinman, S.J., Nather, R.E., & Phillips, T., 1996, PASP, 108, 356

Kurtz, D.W., 1982, MNRAS, 200, 807

Kurtz, D.W., Matthews, J.M., Martinez, P., Seeman, J., Cropper, M., Clemens, J.C., Kreidl, T.J., Sterken, C., Schneider, H., Weiss, W.W., Kawaler, S.D., Kepler, S.O., van der Peet, A., Sullivan, D.J., and Wood, H.J., 1989, MNRAS, 240, 881

Matthews, J.M., Kurtz, D.W., Martinez, P., 1999, ApJ, 511, 422

Tassoul M., 1980, ApJS, 43, 469

Tassoul M., 1990, ApJ, 358, 313

Winget, D.E., Nather, R.E., Clemens, J.C., Provencal, J., Kleinman, S.J., Bradley, P.A., Wood, M.A., Claver, C.F., Grauer, A.D., Hine, B.P., Hansen, C.J., Fontaine, G., Wickramasinghe, D.T., Achilleos, N., Marar, T.M.K., Seetha, S., Ashoka, B.N., O'Donoghue, D., Warner, B., Kurtz, D.W., Buckley, D.A., Vauclair, G., Chevreton, M., Dolez, N., Barstow, M.A., Solheim, J.E., Ulla, A. M., Kanaan, A., Kepler, S.O., Henry, G.A., and Kawaler, S.D., 1991, ApJ, 378, 326